THE EFFECT OF ALTERNATE FREEZING AND THAWING ON THE STRENGTH OF CONCRETE

BY

JAMES FOOK ONN YAPP

B. S. University of Illinois, 1915

THESIS

Submitted in Partial Fulfillment of the Requirements for the

Degree of

MASTER OF SCIENCE

IN CIVIL ENGINEERING

IN

THE GRADUATE SCHOOL

OF THE

UNIVERSITY OF ILLINOIS

1916

UNIVERSITY OF ILLINOIS

THE GRADUATE SCHOOL

June 1, 1916 190

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

JAMES FOOK ONN YAPP

ENTITLED THE EFFECT OF ALTERNATE FREEZING AND THAWING ON THE STRENGTH OF CONCRETE.

BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF Master of Science in Civil Engineering.

A.B. McDaniel
In Charge of Major Work

F.H. Newell
Head of Department

Recommendation concurred in:

Committee
on
Final Examination

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I. INTRODUCTION.

1. STATEMENT OF PROBLEM. During the last fifteen years the use of concrete as a building material has increased to such an extent that to-day, it ranks among the important materials in the field of construction. Concrete has generally shown its adaptability to a wide range of uses, and has exhibited marked durability under severe climatic conditions. On account of keen competition and the demand for quick construction, it is necessary to carry on work continuously throughout the year.

As water is an important constituent of concrete, we can readily appreciate the difficulty of placing concrete in freezing weather. Many structures have failed on account of the concrete having been handled in cold weather in a manner similar to that used under normal temperature conditions. The untimely removal of the forms under such conditions often results in the failure of the structure. To be on the safe side, it would be necessary to leave the forms in place for an indeterminate length of time, probably until the following Spring, since it is difficult to determine, even by the closest inspection, the strength of the concrete under different temperature conditions. Hence, it is desirable to have available, for the engineer, the inspector and the builder, information regarding the strength of concrete under such conditions.

2. PREVIOUS INVESTIGATIONS. About four years ago, tests to determine the influence of temperature upon the strength of concrete were made during the construction of some buildings in

Chicago. Then in the year 1913, a series of tests was performed by Messrs. A. J. Anderson and W. J. Bublitz, senior civil engineering students of the class of 1914, University of Illinois, and furnished the subject matter of their baccalaureate thesis. In 1914, Mr. A. J. Anderson, then a graduate student in the civil engineering department, made another series of tests. All the work mentioned above was done under the supervision of Professor A. B. Mc Daniel of the civil engineering department of the University of Illinois. The results of the tests are published in Bulletin No. 81 of the Engineering Experiment Station of the University of Illinois, and later appeared in a paper prepared and presented by Professor McDaniel before the Twelfth Annual Convention of the American Concrete Institure, which was held at Chicago from February 14-17, 1916.

3. SCOPE OF THE INVESTIGATION. This paper presents a record of a series of experiments, which were made between September, 1915 and February, 1916, by Mr. O. F. Wolf and the writer, under the personal supervision of Professor A. B. McDaniel. This series of tests is divided into two groups; Group I and Group II. Group I has five sets; A, B, C, D, and E, comprising two hundred and twenty-five specimens, and Group II has three sets; F, G, and H, including one hundred and twenty specimesn, thus making a total of three hundred and forty-five specimens.

The specimens were given an initial set under a normal temperature of about 70° F., for various periods, after which they were subjected to alternate freezing and thawing conditions. At the expiration of various storage periods under different temperature conditions, specimens were tested with a standard testing machine for their ultimate compressive strength. It is believed that the results of these tests furnish suggestive information concerning the effect of alternate freezing and thawing upon the strength of concrete, a condition which may ordinarily be obtained in actual practice.

II MATERIALS, FORMING OF TEST PIECES, AND METHODS OF STORING AND TESTING

4. Materials for Concrete. The materials used in the test were the same as for other experimental work in concrete made by the Engineering Experiment Station. The quality of materials may be considered as representative of that used in first class concrete construction in the Middle West.

Cement. The cement for Group I was Universal Portland Cement. Samples of the material were taken and tested for tensile strength at the ages of two days and seven days. The average tensile strength of four neat cement briquettes was 386 lbs. per square inch at the end of two days and an average of five neat cement briquettes was 672 lbs. per square inch at the end of seven days. The initial set occured 1 hr. and 35 minutes after the sample was gauged and the final set took place 2 hrs. and 30 minutes later. See Table I, page 4.

Cement. The cement used for making the specimens of Group II was Universal Portland Cement. Samples of the cement were taken and tested for tensile strength at the ages of seven days and twenty-eight days. The average tensile strength of five neat cement briquettes was 606 lbs. per square inch at seven days and 716 lbs. per square inch at twenty-eight days and the average strength of five 1:3 mortar briquettes of standard Ottawa sand was 236 lbs. per square inch at seven days and 299 lbs. per square inch at twenty-eight days.

TABLE I

Test of Cement for Group I

Temp. of Room		25.0° C.
" " Water		24.8° C.
" " Moist Closet		24.2° C.

Consistency

Gms. of Water	Per Cent. of Water	Penetration
115	23.0	17
108	21.2	5
112	22.4	10

Time of Set

Gauged	Initial	Final
11:00	12:35	3:05
	1 hr. 35 min.	4 hrs. 5 min.

Strength

	24 hr. neat	7 days neat
	395	660
	365	670
	410	690
	375	685
		655
	4)1545	5)3360
Average	386	672

The amount of water used to give normal consistency was 23.2 per cent. Initial set occurred 2 hrs. and 55 minutes after the sample was gauged and final set took place 3 hrs. later. An average of five briquettes for a one part cement and three parts standard Ottawa sand mortar gave a tensile strength of 236 lbs. per square inch at seven days and 299 lbs. per square inch at twenty-eight days. The results of the test are given in Table II, pages 6 and 7.

Sand. The sand for both Groups I and II came from a deposit of glacial drift near the Wabash River, at Attica Indiana. The material was clean and well graded. An average of five briquettes of one part cement and 3 parts sand gave a tensile strength of 283 lbs. per square inch at seven days and an average of four briquettes of the same materials and the same mixture gave a tensile strength of 375 lbs. per square inch at twenty-eight days. The results of the test are given in Table II, pages 6 and 7. The results of the mechanical sieve analysis test are given in Table III page 8 and in Fig. 1 on page 10.

Gravel. The gravel used in Groups I and II came from a deposit of glacial drift near the Wabash River at Attica, Indiana. It contained 57 per cent. of material smaller than 1/2 inch and 8.1 per cent. of material smaller than 1/4 in. It contained 47 per cent. voids. The results of the mechanical sieve analysis rest are given in Table IV, page 9 and in Fig. 1 on page 10.

5. CONCRETE. All the concrete used was composed of (a) 1 part cement, 1 part sand and 2 parts gravel by weight or 1 part cement, 1.2 part sand and 2.2 parts gravel be volume, (b) 1 part cement, 2 parts sand and 4 parts gravel by weight or 1 part cement, 2.4 parts sand and 4.4 parts gravel by volume, (c) 1 part cement, 4 parts sand and 8 parts gravel by weight or 1 part cement, 4.8

TABLE II

GROUP II

Tensile Strength of Cement

Temperature of Air 25.6° C.

" " Water 20.0° C.

Consistency

Water		Penetration
Grams	Per cent.	
117.5	23.5	12.0 mm.
116.0	23.2	10.0 "

Time of Set

Gauged	Initial	Final
11:25	2:20	5:20
	2 hrs. 55 min.	5 hrs. 55 min.

Tensile Strength

7 Days

	Neat	1:3 Standard Ottawa Sand	1:3 Attica Sand	Specification for Universal Portland Neat	Specification for Universal Portland 1:3 Standard Ottawa Sand
	625	220	305		
	595	245	270		
	575	245	290		
	620	225	265		
	615	245	285		
	5)3030	5)1180	5)1415		
Av.	606	236	283	500	200

Twenty-eight Days

Neat	1:3 Standard Ottawa Sand	1:3 Attica Sand	Specification for Universal Portland: Neat	Specification for Universal Portland: 1:3 Standard Ottawa Sand
705	290	400		
715	310	385		
730	300	350		
695	300	365		
735	285			
5)3580	5)1495	4)1500		
716	299	375	600	275

TABLE III

Sieve Analysis of Sand

Sieve No.	Diameter Opening	Grams Retained	Grams Passing	Per cent. Passing
	0.20	32.0	966.0	96.6
5	0.16	65.8	900.2	90.0
8	0.093	117.8	782.4	78.2
20	0.034	378.0	404.4	40.4
40	0.015	240.0	164.0	16.4
60	0.009	112.0	52.0	5.2
74	0.0078	18.0	34.0	3.4
100	0.0055	14.0	20.0	2.0
Pan	0.000	20.0	0.0	0.0
		997.6		

TABLE III

Sieve Analysis of Gravel

Sieve No.	Diameter Opening	Grams Retained	Grams Passing	Per Cent. Passing
1.5	1.50	0.	4998.	100.0
1.0	1.00	160.	4838.	97.0
.66	0.66	1498.	3340.	67.0
.50	0.50	490.	2950.	59.2
.25	0.25	2390.	560.	11.2
.2	0.20	231.	229.	4.6
5.0	0.16	150.	79.	1.6
8.0	0.093	40.	39.	0.7
20.0	0.034	12.	27.	0.54
40.0	0.015	2.	25.	0.50
60.0	0.009	22.	23.	0.46
74.0	0.0078	1.	22.	0.44
100.0	0.0055	1.	21.	0.42
Pan	0.00	21.	00.	0.00
		4998		

TABLE IVa

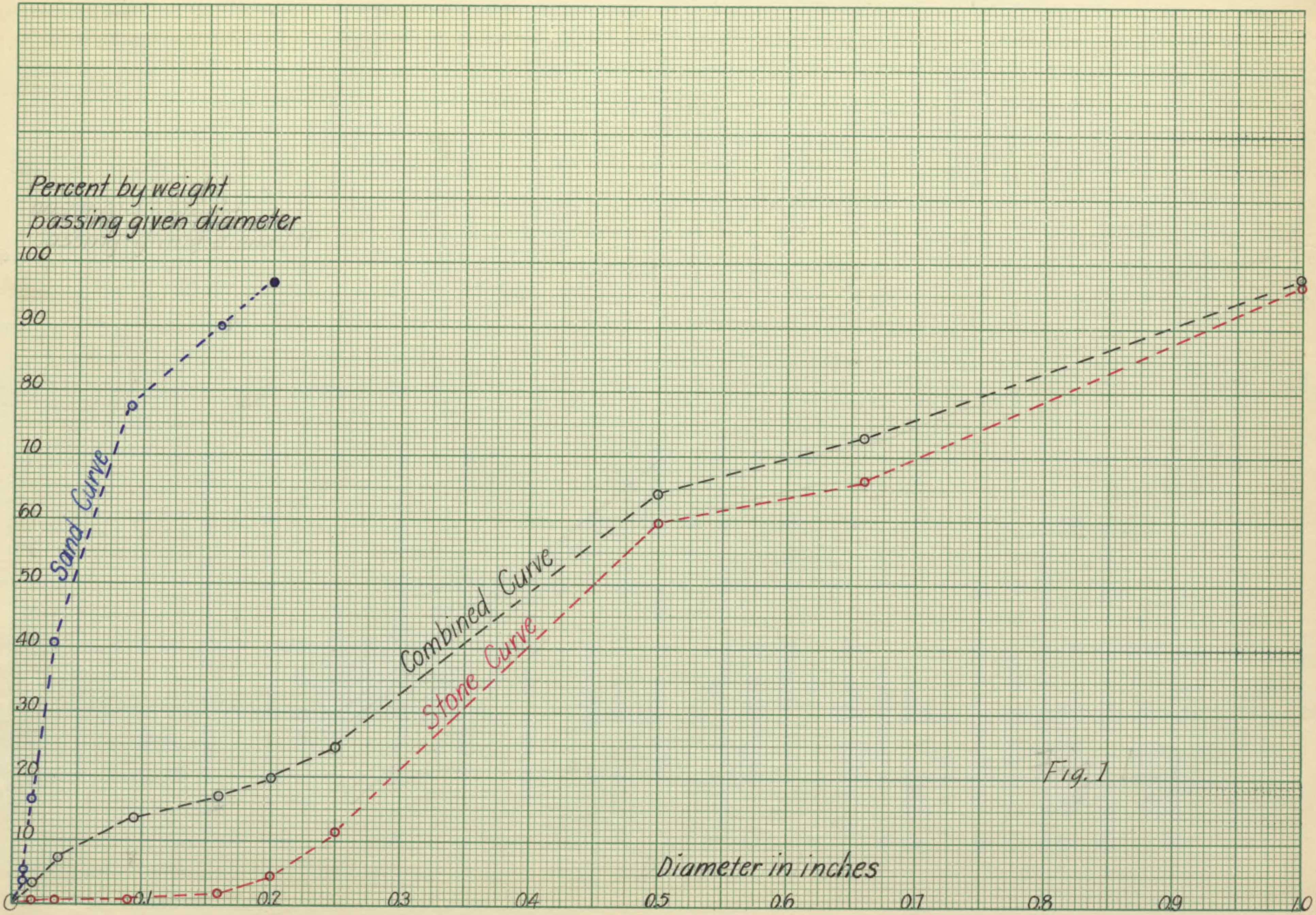
Mechanical Analysis of Combined Sand and Gravel

Sieve No.	Diameter Opening	Grams Retained	Grams Passing	Per cent. Passing
1.2	1.5	0.	5995.6	100.0
1.0	1.0	160.	5835.6	97.5
0.66	0.66	1498.	4337.6	73.0
0.50	0.50	490.	3847.6	64.2
0.25	0.25	2390.	1457.6	24.4
0.20	0.20	263.	1194.6	19.8
5	0.16	215.8	978.8	16.3
8	0.09	157.8	821.0	13.7
20	0.034	390.0	431.0	7.2
40	0.015	242.0	190.0	3.18
60	0.009	114.0	71.0	1.18
74	0.0078	19.0	56.0	0.90
100	0.0055	15.0	41.0	0.68
Pan	0.0000	41.0	00.0	0.00
		5995.6		

TABLE IVb

Test for Voids in Gravel

Per Cent. of Water in Gravel	Volume of Container cc.	Volume of Water Filling Voids	Per cent. of voids
0	2650	1253	47


Percent by weight
passing given diameter
100
90
80
70
60
50
40
30
20
10
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Diameter in inches
Sand Curve
Combined Curve
Stone Curve
Fig. 1

parts sand and 8.8 parts gravel by volume. The materials for each specimen were weighed out separately two days before molding, and were thoroughly dried. The amount of materials necessary for the specimens are given in Table V, page 14.

Making the Concrete. The concrete was mixed by hand. The cement and sand were placed in a pan, then thoroughly mixed and spread in a layer about half an inch in thickness. Upon this layer, the gravel was then placed and all the ingredients were finally and thoroughly mixed, after which they were dumped into the mixing pan and collected in a cone-shaped pile. The materials were then carefully and thoroughly mixed with the necessary amount of water. Before each molding period, a test was performed to determine the consistency of the concrete according to the specifications of the American Society for Testing Materials. For the 1:4:8 mixture more water than that required by the above specifications was used on account of the difficulty in molding a rather dry and lean mixture. In this case the same quantity of water as for the 1:1:2 mixture was used. See Table V, page 14.

6. MOLDING AND STORAGE OF TEST SPECIMENS. Table VI pages 15 and 16 gives the details of the classification of test specimens according to form and storage conditions.

Form. All test specimens were 6 x 12 cylinders; six inches in diameter and 12 inches in length. The forms were made of 6 inch cast iron pipes, cut to the desired length, with a single longitudinal slit. On each side of the slit and parallel with it, one leg of a structural steel angle, 2 x 2 x 1/16"-12" long was riveted. Through the outstanding legs of the angles at the quarter point from each end, 1/4 inch holes were drilled through which bolts were inserted. On each end of the bolts, wing-nuts were attached..

By tightening the wing-nuts on the bolts, the slits on the molds were closed. Each mold was then thoroughly oiled on the inside and one end of it placed upon a sheet of waxed paper which rested upon a horizontal glass plate 1/4 inch thick. The waxed paper served to prevent the cement adhering to the glass plate and to furnish a smooth bearing surface.

Molding. The concrete was put into the molds, a scoop-full at a time, an average of six scoops was required to fill each mold. After each scoopfull, the concrete in the mold was slightly tamped with a 1/4 inch iron rod and the aggregates were distributed as evenly as possible. The process was continued until each mold was completely filled. A trowel was used to smooth the surface. After an initial set of about 3 hrs. the top of the specimen would settle about 1/4 of an inch. A rather wet neat cement mortar was then placed on the top and covered with a piece of waxed paper. A glass plate was next placed over the waxed paper after which a direct pressure was applied to the center of the plate until the plate received a perfect bearing upon the circumference of the cylindrical mold. The specimen was then labeled and left undisturbed until the schedule called for its removal. The whole process of preparing the specimen from the dry mixing of the materials to the finish of placing same into the molds occupied an average time of 8 minutes. The specimens of Group I were molded in the concrete room of the Engineering Experiment Station at an average temperature of 68° Fahrenheit and were moved to their respective storage rooms after an initial set of about two days. The specimens of Group II were molded under a normal temperature of about 70° F. in the storage room of the Twin City Ice and Cold Storage Plant.

Storage. All the specimens were stored at the Twin City Ice and Storage Plant where two rooms were used, one having a normal temperature of about 70° F. and the other a temperature of about 20° F. The specimens were handled as carefully as possible and were covered with damp burlap so as to maintain a uniform moisture condition. In Group I, all specimens were moved to their respective storage rooms after the molds had been taken off, but in Group II, those having had an initial set of from 4 to 12 hrs. were shifted with the molds, which were removed about 4 days later. Table VI, page 15 gives the condition of storage of the specimens.

The storage temperatures were determined daily by readings of maximum and minimum thermometers placed alongside the specimens. To obtain the internal temperatures of the concrete, thermometers were inserted within special specimens of which three were made in Group I and three in Group II. The temperatures of Group I are given in Table VII, page 17, and those of Group II in Table VII, page 18.

7. METHOD OF TESTING. All the specimens were taken from their storage places to the Laboratory of Applied Mechanics of the University of Illinois, where they were immediately weighed, measured, their bearing surfaces coated with plaster of Paris when necessary and tested with a Standard Olsen testing machine of 200,000 lbs. capacity for their ultimate compressive strength.

TABLE V

Data Concerning Molding of Specimens

Form	Group	Set	No.	Av. Time of molding	Av. Temp. Room	Av. Temp. Concrete	Weight of 1:1:2 Cement lbs.	Weight of 1:1:2 Sand lbs.
6x12	I	A	42	6 hrs.	68	67	6.5	7.87
cylin-		B	42	6 "	68	68	"	"
ders		C	42	5.5"	71	70	"	"
		D	42	5 "	71	71	"	"
		E	42	5 "	70	70	"	"
6x12	II	F	39	6 "	70	69	"	"
cylin-		G	39	5.5"	69	69	"	"
ders		H	39	6 "	71	71	"	"

Materials Gravel lbs.	1:2:4 Cement lbs.	1:2:4 Sand lbs.	1:2:4 Gravel lbs.	1:4:8 Cement lbs.	1:4:8 Sand lbs.	1:4:8 Gravel lbs.	Per cent. of water by weight 1:1:2	1:2:4	1:4:8
14.30	3.7	8.95	16.28	2.0	9.68	17.60	9.81	9.31	8.84
"	"	"	"	"	"	"	"	"	"
"	"	"	"	"	"	"	"	"	"
"	"	"	"	"	"	"	"	"	"
"	"	"	"	"	"	"	"	"	"
"	"	"	"	"	"	"	"	"	"
"	"	"	"	"	"	"	"	"	"
"	"	"	"	"	"	"	"	"	"

TABLE VI.

Description of Test Specimens

Series	Group	Set	Specimens No.	Specimens Form	#Number and Age of Specimen when tested	
1915	I	A	42	6x12 cylinders	2 days at 70° F.	
		B	42		2 " " "	, 3 reversals at 25°F. and 70° F.
		C	42		6 " " "	
		D	42		6 " " "	3 reversals at 25°F. and 70° F.
		E	42		10 " " "	
					10 " " "	3 reversals at 25°F. and 70° F.
					14 " " "	
					14 " " "	3 reversals at 25°F. and 70° F.
					2 " " "	3 reversals at 25°F. and 70° F. 20 days at 70° F.
					6 " " "	3 reversals at 25°F. and 70° F. 16 days at 70° F.
					10 " " "	3 reversals at 25°F. and 70° F. 12 days at 70° F.
					14 " " "	3 reversals at 25°F. and 70° F. 8 days at 70° F.
					28 " " "	
1916	II	F	39	6x12 cylinders	4 hrs. at 70° F.,	1 reversal at 25°F. and 70° F.
		G	39		8 " " "	1 reversal at 25°F. and 70° F.
		H	39		12 " " "	1 reversal at 25°F. and 70° F.
					24 " " "	1 reversal at 25°F. and 70° F.
					4 " " "	2 reversals at 25°F. and 70° F.
					8 " " "	2 reversals at 25°F. and 70° F.

12 hrs. at 70° F.,	2 reversals at 25°F. and 70° F.
24 " " "	2 reversals at 25°F. and 70° F.
6 days " "	
7 " " "	
12 " " "	
13 " " "	
28 " " "	

....

#In each set were 13 different cases of storage as noted. There was one specimen for each case, for each mix of concrete except for the case of 28 days at 70° F. in Group I where two specimens were used.

TABLE VII

Temperature Readings[1]

Group I

	Hot Room										Cold Room			
	S End		N End		Room		Specimen Number							
	Max	Min	Max	Min	S End	N End	1A15	5A15	5B15	5C15	Max	Min	Room	1A17
10-14			79	52		66	24				45	23	24	30
10-15			88	62		70	26				27	22	25	22
10-16			77	59		67	25				26	23	24	25
10-17	73	65	78	60	69	69	26				28	24	26	21
10-18	80	70	83	71	75	77	23				30	25	27	20
10-19	81	65	76	70	68	73	24				29	24	25	21
10-20	68	68	65	69	68	65	17				28	25	26	28
10-21	69	69	63	67	67	67	22				28	25	25	25
10-22	70	70	70	70	70	68	22				25	25	26	25
10-23	70	56	68	66	69	66	21				28	25	25	24
10-24	68	68	70	70	69	70	23				28	28	26	24
10-25	70	68	68	68	69	68	21				28	25	25	24
10-26	72	68	72	67	69	70	23				30	26	28	24
10-27	70	65	70	64	68	69	21				28	24	27	25
10-28	68	66	70	68	68	69	22				27	24	26	25
10-29	69	64	72	78	66	72	21				29	24	27	25
10-30	73	73	68	66	63	68	22	22	22	21	29	24	26	25
10-31	68	64	73	67	66	70	23	22	22	22	26	24	26	25
11- 1	68	66	70	68	67	69	23	22	22	22	28	26	26	25
11- 2	69	63	70	64	65	67	22	25	25	25	28	25	26	24
11- 3	66	65	71	67	66	70	24	26	25	25	30	24	25	25
11- 4	67	64	70	67	65	70	22	25	25	25	26	24	25	25
11- 5	68	66	72	70	67	72	23				29	25	26	25
11- 6	69	67	72	70	68	71	24	25	25	24	28	25	28	26
11- 7	69	68	71	69	69	70	25	24	25	24	30	26	28	26
11- 8	71	68	69	66	68	67	23	22	22	21	28	27	28	28
11- 9	69	66	68	64	66	65	23	22	23	22	30	27	28	26
11-10	67	65	66	64	65	65	23	23	23	22	29	26	28	26
11-11	67	65	66	64	66	65	24	24	24	23	30	27	30	28
11-12	68	65	65	63	66	64	23	23	23	22	31	27	28	28
11-13	67	63	66	63	64	65	24	24	24	24	29	27	28	26
11-14	66	64	65	64	65	65	23	22	22	21	29	25	27	26
11-15	66	63	65	61	65	63	23	23	23	23	29	24	26	26
11-16	84	65	82	65	77	76	25	24	25	24	27	24	26	26
11-17	83	72	82	71	73	72	25	25	25	24	27	24	26	25
11-18	80	72	80	73	75	76	27	26	26	26	28	24	26	25
11-19	77	69	80	69	76	76	25	25	25	25	27	24	27	25
11-20	78	64	80	70	75	77	26	25	25	26	28	24	25	25
11-21	78	64	80	61	72	76	25	25	26	25	27	24	24	25
11-22	82	70	86	72	77	83	25	25	26	25	28	24	24	25
11-23	80	71	113	68	77	84	27	26	27	27	27	24	25	25
11-24														
11-25	In cold room													
11-26														

[1] All values are in Degrees Fahrenheit.

TABLE VIII

Temperature Readings*

Group II

Date		Hot Room				Cold Room			
Jan.	1A14	Max	Min.	Av. Room	1B14	Max	Min	Av. Room	1C14
14	20	70	70	70		51	22	23	
15	20	70	64	70	23	51	20	23	18
16	20	71	68	71	23	24	18	22	18
17	20.5	74	60	65	19	22	18	18	17
18	18	68	68	68	17	18	18	18	17
19	18	66	60	64	17	18	18	18	23
20	15	64	58	60	17	20	18	18	22
21	20.5	65	60	65	22	18	18	18	23
22	20	66	62	64	22	22	20	18	17
23	20.5	67	62	63	22	22	18	18	22
24	20	66	64	63	23	22	20	18	22
25	18	64	62	62	23	22	20	18	22
26	18	62	61.5	65	23	22	20	18	22
27	18	65	64	64	23	22	20	18	23
28	21	67	65	65	23	22	20	18	23
29	20	67	64	64		22	20	18	23
30	21	68	66	65		22	20	18	23
31	22	68	66	66		22	20	18	22
Feb.									
1	20.5	64	62	62		22	20	18	22
2	20	64	62	62		22	20	18	22
3	20.5	65	64	63		22	20	18	22
4	20	64	62	62		22	20	18	22
5	21	65	63	62		22	20	18	22
6	21	66	64	62		22	20	18	22
7	22	68	60	66		22	20	18	22
8	22	69	68	65		22	20	18	22
9	21	66	65	65		22	20	18	22
10	22	67	66	66		22	20	18	22
11	22	68	66	65		22	20	18	22
12	23	68	67	66					
13	22	69	66	67					
14									
15	23	69	68	67					
16									
17	23	70	66	68					
18									
19	22	71	65	70					
20									
21	23	71	68	67					
22									
23	22	70	69	66					
24									
25	22	69	67	68					

No specimens in cold room

*All values are in Degrees Fahrenheit.

III. DATA OF TESTS

8. OBSERVED RESULTS. The results of the tests are given in Tables V to VIII, pages 14 to 18; Table IX, page 22; Table XII, page 31; and in Figs. 2 to 7, pages 25, 26, 27, 33, 34 and 35.

IV. DISCUSSION OF DATA

9. GROUP I. The results of the tests of Group I are given in Table IX page 22, and shown in Figs. 2, 4 and 5, pages 25, 26 and 27, for the 1:1:2, 1:2:4 and 1:4:8 mixtures respectively. In each Figure, curve 1 shows the relation between strength and age under normal temperature conditions. Curve 2 shows the relation between strength and age for different initial storage periods at a normal temperature followed by a period of three reversals, each reversal being equivalent to one day in a normal temperature of about 70° F., succeeded by one day in a freezing temperature of about 20° F. The data are also given in Table I, page 23. Curves 2, 4, 5 and 6 show the effect upon the strength at the age of twenty-eight days of intermediate periods of three reversals, after initial normal temperature storage periods of two, six, ten and fourteen days. The data are shown in Table IX, page 24.

The average temperature for the normal temperature and freezing temperature storage rooms are shown at the top of Figs. 2, 3 and 4, pages 25, 26 and 27. These curves represent the average temperatures of the five sets. The storage temperatures were nearly uniform, there being a total variation of only four degrees in the normal temperature and of two degrees in the freezing temperature.

A reference to the plotted values for Curve 1 of Figs. 2, 3, and 4, pages 25, 26 and 27 shows a high rate of increase in strength for the first six days, followed by a lessened increase of strength during the next four days and then a higher rate of increase during the succeeding four days. This slump in the test values indicates the effect of a quick setting cement; the concrete attaining a high strength at an early age. See Table IX, page 22.

A study of Curve 2, Figs. 2 , 3 and 4 , pages 25,26 and 27 and Table X page 23, shows the relative strength for ages of from seven to twenty-one days for specimens which have been stored at a normal temperature and those which have been stored at different periods under a normal temperature followed by a three reversal period. For all mixtures the strength after an initial normal temperature storage of two days and a three reversal period is about 89% of the strength for eight days at a normal temperature. For the 1:1:2 mixture the loss of strength decreased with the increase of age of the specimens. For the 1:2:4 mixture there is a slight increase in the loss of strength during the same period. For the 1:4:8 mixture the loss of strength is practically the same for all ages.

An inspection of Curves 3, 4, 5 and 6 of Figs. 2 , 3 and 4 , pages 25,26 and 27, and Table XI, page 24, shows the effect upon the strength of twenty-eight day specimens due to the insertion of a three day reversal period after an initial storage period of different lengths at a normal temperature. With the exception of the specimens stored for an initial period of two days at a normal temperature there is a gain in the strength with the length of the initial storage period. The relatively high strengths for all mixtures at the two day initial storage period is probably due to the quick setting property of the cement. For the 1:1:2 mixture the retarding effect of the reversals of temperature after initial normal temperature storage at six and ten days is about 6% of the strength for twenty-eight days at a normal temperature; the retarding effect being nothing for an initial normal temperature storage period of fourteen days. For the 1:2:4 mixture the retarding effect of the temperature reversals after initial normal temperature storage at six, ten and fourteen days was about 14, 8 and 7% respectively of the strength for twenty-eight days at a normal temperature. For the 1:4:8 mixture the retarding influence of the three day reversal period after initial normal temperature storage at six, ten and fourteen days was about 8, 8 and 6% respectively of the strength for twenty-eight days at a normal temperature.

TABLE IX

Test Data

Group I

Age	1:1:2					1:2:4					1:4:8				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
2 Days at 70 F.		1680	1340 1460	1620	1270	680	800	540 650	680	560	160	170	120 160	150	190
2 Days at 70 F. 3 Reversals at 25 C. and 70 F.	2480	2590	2830 2400		2210	1330	1380	830 1200 1280	1200	1150	480	370	280 350	340	340
6 Days at 70 F.	2950	2700	2440 2650	2820	2200	1640	1070	800 1130	1260	890	340	380	250 330	290	330
6 Days at 70 F. 3 Reversals at 25 C. and 70 F.	3070	2850	2140 2750	3170	2530	1730	1260	1080 1330	1450	1140	430	390	300 280	440	340
10 Days at 70 F.	3130	2750	2100 2750	2510	2960	1790	1100	1120 1330	990	1550	490	440	260 390	410	370
10 Days at 70 F. 3 Reversals at 25 C. and 70 F.	3300	3430	2720 3050	2610	2980	1800	2290	1400 1690	1400	1712	590	460	500	480	490
14 Days at 70 F.	3000	3610	3030 3210	3640	2780	1840	1830	1540 1680	1540	1640	420	690	300 455	500	480
14 Days at 70 F. 3 Reversals at 25 C. and 70 F.	3520	3580	3030 3280	3200	3060	1670	1440	1540 1580	1900	1560	350	660	410 560	670	490
2 Days at 70 F. 3 Reversals at 25 C. and 70 F. 20 Days at 70 F.	3130	4330	3580 3560 3370 3160	4000	2770	2560	3230	1680 2070 1980	2000	1900	880	530	590 670 680	670	700
6 Days at 70 F. 3 Reversals at 25 C. and 70 F. 16 Days at 70 F.	3730	2830	3350 3190	4130	2530	2300	1590	1410 1700 1850	1850	1650	650	690	450 630	740	630
10 Days at 70 F. 3 Reversals at 25 C. and 70 F. 12 Days at 70 F.	3100	3500	2480 3210	3780	3210	2660	2240	1960 1980	1400	2160	670	880	570 660 635	560	640
14 Days at 70 F. 3 Reversals at 25 C. and 70 F. 8 Days at 70 F.	2410	4030	3480 3420	3930	3350	2060	2060	2100 1990	1780	1930	540	840	610 650	710	500
28 Days at 70 F.	3510 3600	3020 2750	3310 3720 3220 3420	3480 3230	2780 2790	2330 2340	2420 2360	1970 2000 2150	2100 2120	1900 1950	650 640	800 940	540 600 690	730 690	640 670

TABLE X

Strengths at Various Ages and Under Different Storage Conditions

Group I

Age in Days

Storage Conditions	Mixtures	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Normal Temperature	1:1:2		1480	1700	2090	2280	2420	2580	2700	2800	2900	3000	3080	3150	3210
	1:2:4		650	760	865	960	1060	1165	1220	1310	1400	1460	1540	1600	1680
	1:4:8		160	200	240	270	300	335	360	390	420	440	460	490	510
Initial Normal Temperature and 3 Reversals	1:1:2								2400	2490	2580	2660	2750	2830	2900
	1:2:4								1080	1160	1240	1300	1360	1420	1470
	1:4:8								320	345	370	395	420	440	460
Loss of Strength due Reversals	1:1:2								300	310	320	340	330	320	310
	1:2:4								140	150	160	160	180	180	210
	1:4:8								40	45	50	45	40	50	50
Loss of Strength due to Reversals in per cent.	1:1:2								11.1	11.2	11.3	11.3	10.8	10.1	9.7
	1:2:4								11.4	11.4	11.4	11.0	11.7	11.2	12.5
	1:4:8								11.1	11.5	11.9	10.2	8.7	10.2	9.8

Storage Conditions	Mixtures	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Normal Temperature	1:1:2	3250	3280	3300	3325	3350	3360	3370	3380	3390	3400	3410	3415	3418	3470
	1:2:4	1710	1770	1810	1860	1900	1940	1980	2000	2030	2060	2080	2110	2130	2150
	1:4:8	525	540	560	570	590	600	610	625	635	650	660	670	680	690
Initial Normal Temperature and 3 Reversals	1:1:2	2980	3050	3110	3180	3230	3260	3310							
	1:2:4	1520	1570	1610	1650	1690	1720	1750							
	1:4:8	480	500	520	530	550	560	575							
Loss of Strength due Reversals	1:1:2	270	230	190	145	120	100	60							
	1:2:4	190	200	200	210	210	220	230							
	1:4:8	45	40	40	50	40	40	45							
Loss of Strength due to Reversals in per cent.	1:1:2	8.3	7.0	5.7	4.4	3.6	3.0	1.8							
	1:2:4	11.1	11.3	11.4	11.5	11.1	11.3	11.6							
	1:4:8	8.6	7.4	7.1	8.8	6.8	6.7	7.4							

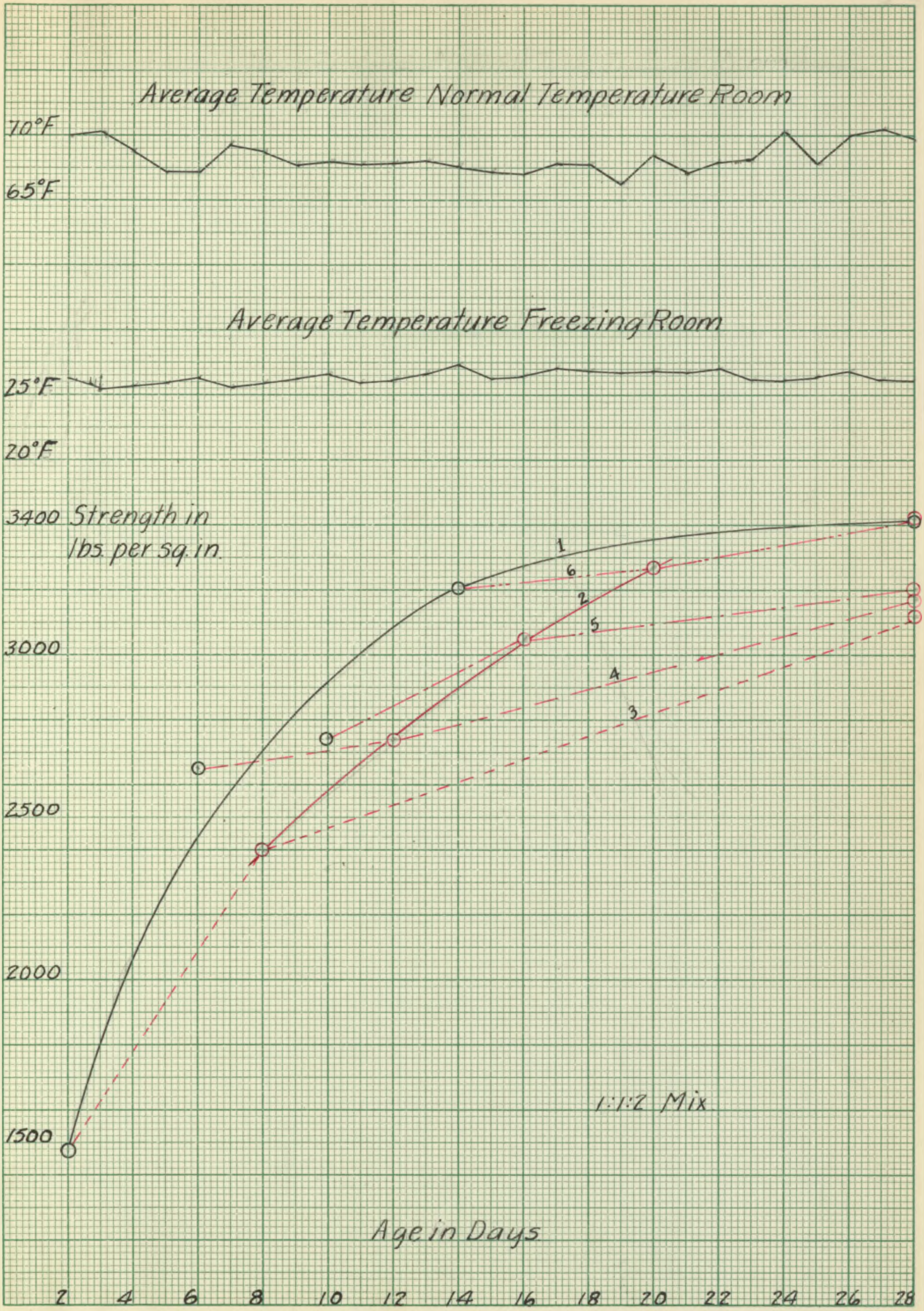
TABLE XI

Group I

Strengths at Twenty-eight Days Under

Different Storage Conditions

Storage Conditions	Mixture			Loss of Strength					
				1:1:2		1:2:4		1:4:8	
	1:1:2	1:2:4	1:4:8	Lbs.	%	Lbs.	%	Lbs.	%
28 Days at Normal Temperature	3420	2150	690						
2 Days at Normal Temperature. 3 Reversals. 20 Days at Normal Temperature.	3370	1950	620	50	7.2	200	9.3	70	10.1
6 Days at Normal Temperature. 3 Reversals. 16 Days at Normal Temperature.	3190	1850	630	230	3.3	300	13.9	60	8.7
10 Days at Normal Temperature. 3 Reversals. 12 Days at Normal Temperature.	3210	1980	635	210	3.02	170	7.9	55	8.0
14 Days at Normal Temperature. 3 Reversals. 8 Days at Normal Temperature.	3420	1990	650	0	0	160	7.4	40	5.8


Average Temperature Normal Temperature Room
70°F
65°F
Average Temperature Freezing Room
25°F
20°F
3400 Strength in
lbs. per sq. in.
3000
2500
2000
1500
1
6
2
5
4
3
1:1:2 Mix
Age in Days
2
4
6
8
10
12
14
16
18
20
22
24
26
28

Fig, 2.

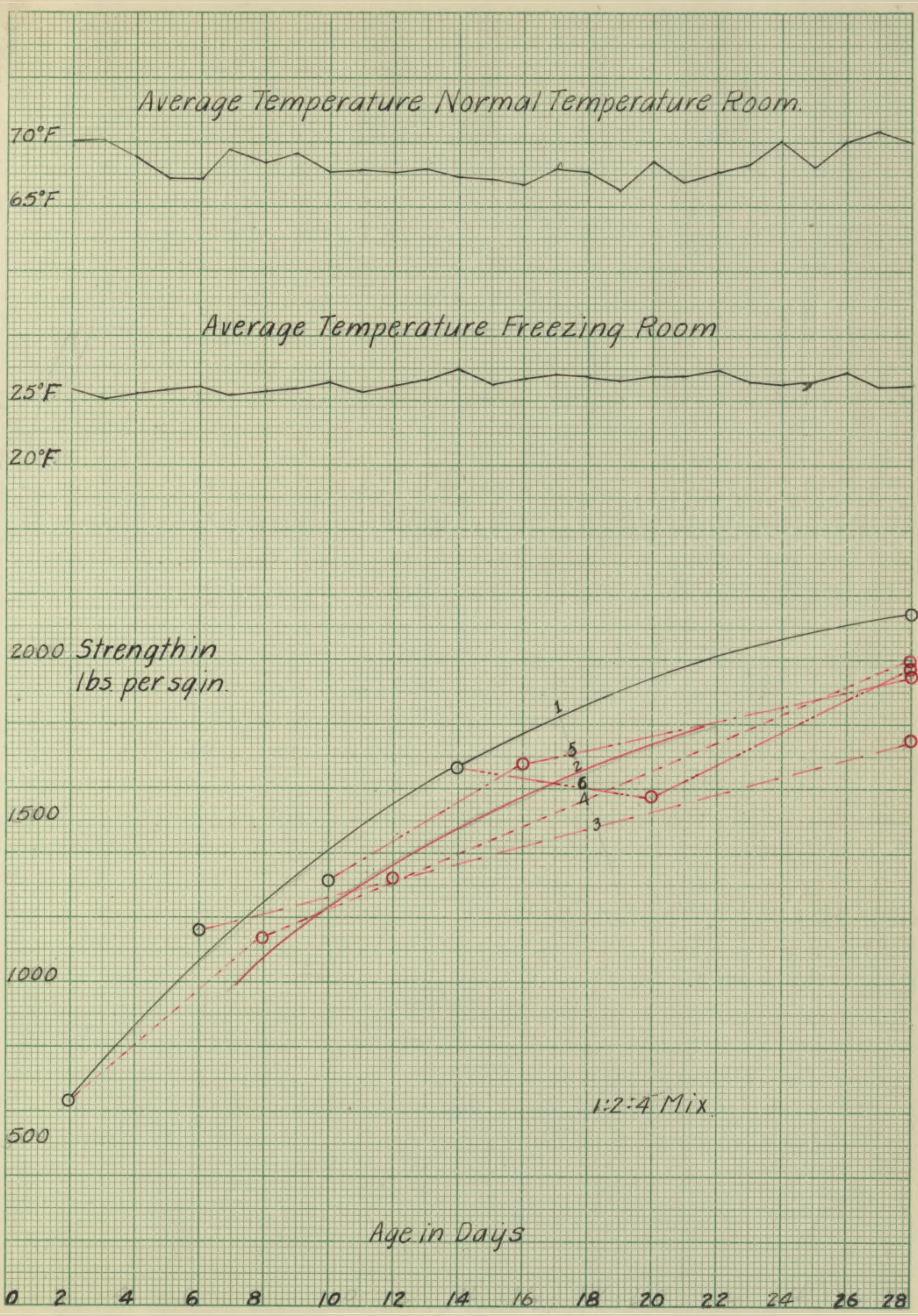

Average Temperature Normal Temperature Room.
70°F
65°F
Average Temperature Freezing Room
25°F
20°F
2000 Strength in lbs. per sq.in.
1500
1000
500
1
5
2
6
4
3
1:2:4 Mix
Age in Days
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28

Fig. 3.

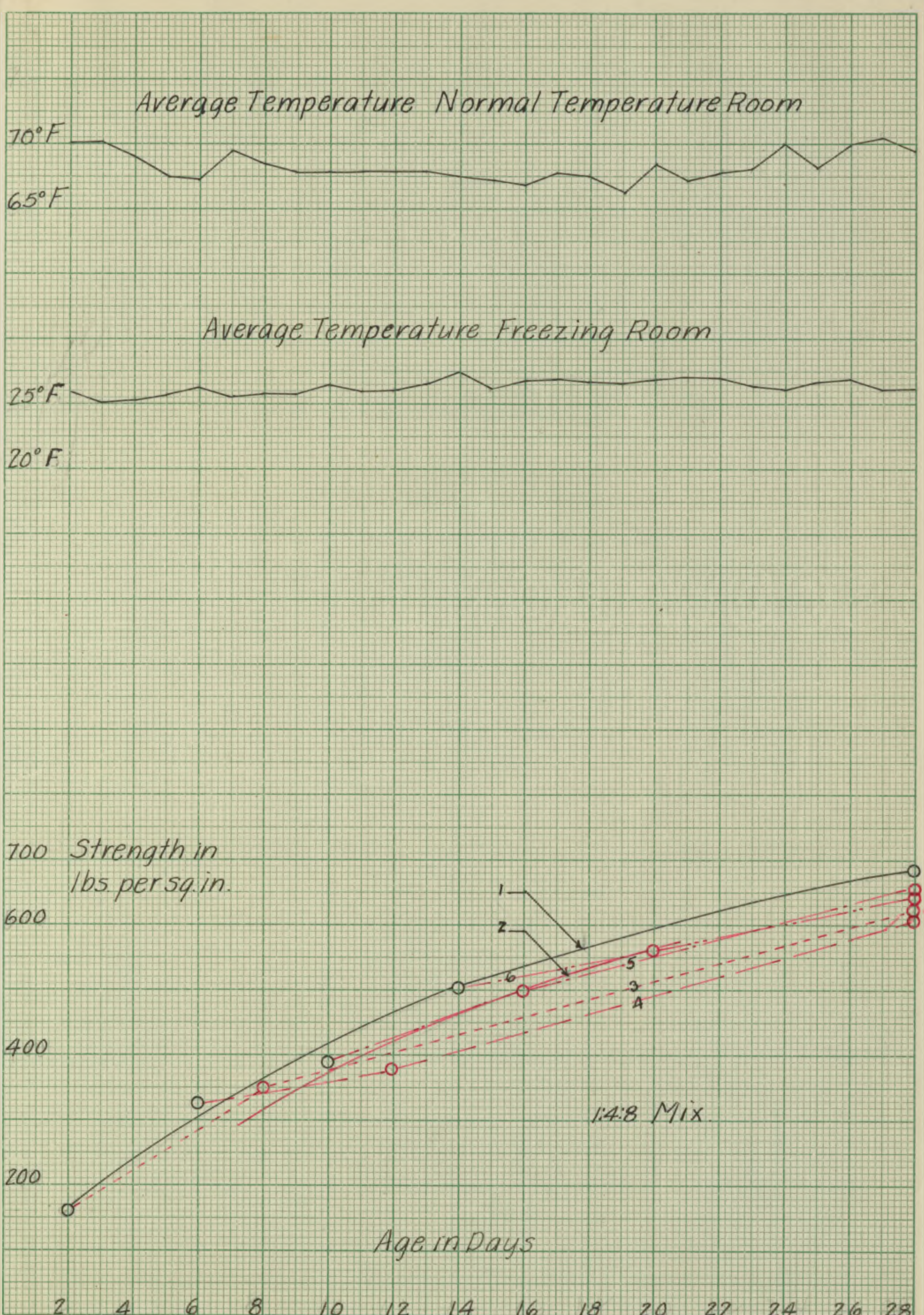

Average Temperature Normal Temperature Room
70°F
65°F
Average Temperature Freezing Room
25°F
20°F
700
Strength in lbs per sq. in.
600
400
200
1
2
5
6
3
4
1:4:8 Mix.
Age in Days
2
4
6
8
10
12
14
16
18
20
22
24
26
28

Fig. 4.

Characteristics of Failures

IV. DISCUSSION OF DATA

10. GROUP II. The results of the test of Group II are given in Table XII, page 31, and shown in Figs. 5, 6 and 7, pages 33, 34 and 35, for the 1:1:2 , 1:2:4 and 1:4:8 mixtures respectively. In each figure, Curve 1 represents the relation between the strength and age for specimens stored at a normal temperature, and Curves 2 and 3 represent the relation between the strength and age for specimens having had different storage periods under normal temperature plus one and two reversals respectively. Two days in normal temperature of about 70° F. and two days in freezing temperature of about 20° F. constituted one reversal.

The average temperature for the normal and freezing rooms are shown at the top of Figs. 5, 6 and 7 pages 33, 34, and 35. The curves are plotted on the basis of three sets since in this group, an average of three specimens was used. The temperature in the normal temperature room shows but a slight variation, and that of the freezing room is practically constant.

In examining the plotted values for Curve I of Figs. 5, 6 and 7, pages 33, 34 and 35 the same general characteristics prevail as in those of Group I, Figs. 3, 4 and 5, pages 25, 26 and 27,-- i. e., the high rate of increase in strength for the first six days followed by a lesser rate of increase and then a higher rate for a period of about four days. In the case of the 1:4:8 mixture, the above mentioned characteristic is not evident. There appears to be a nearly uniform increase of strength for the twenty-eight days.

The low rate of increase of strength during the first six days for the 1:4:8 mixture is probably due to the excess of water added in the mixing to facilitate molding.

Curves 2 and 3 pages 28,29 and30 and Table XIII page 32 show the relative strengths for the ages of 4 to 5 days and 8 to 9 days respectively. The results show that for any particular mixture, the loss in strength due to the alternate freezing and thawing conditions decreases as the length of the initial storage period at a normal temperature increases.

An inspection of Table XIII, page 32 shows that the percentage of loss of strength due to alternations of temperatures above and below freezing, varies with the richness of the mixture, being greatest for the 1:4:8 mixture and least for the 1:1:2 mixture. In the case of the two reversals, the percentage of loss for the two shorter initial storage periods is about the same for the 1:2:4 and 1:4:8 mixtures. This apparent anomalous condition is probably due to the low rate of increase in strength of the 1:4:8 concrete during the first week. The percentage loss of strength in the case of the 1:1:2 mixture is practically the same for one and two reversals, while for the leaner mixtures, 1:2:4 and 1:4:8, the percentage loss of strength is greater for the two reversals than for one reversal.

TABLE XII
Test Data
Group II

AGE	1:1:2			1:2:4			1:4:8		
	1	2	3	1	2	3	1	2	3
4 hrs. at 70° 1 reversal	680	480 760	1130	175	85 180	280	0	21 40	106
8 hrs. at 70° 1 reversal	780	870 840	880	270	120 230	300	40	42 50	70
12 hrs. at 70° 1 reversal	880	935 890	820	480	270 390	310	78	53 80	110
6 days at 70°	1590	1620 1770	2050	555	500 600	740	150	140 160	198
24 hrs. at 70° 1 reversal	725	1200 1060	1260	320	235 350	500	55	90 90	113
7 days at 70°	1550	1500 1540	1580	465	450 530	665	230	140 210	255
4 hrs. at 70° 2 reversals	860	810 1080	1575	165	195 250	400	0	57 60	145
8 hrs. at 70° 2 reversals	1220	1230 1290	1440	360	250 220	310	65	80 100	140
12 hrs. at 70° 2 reversals	1050	1250 1260	1490	450	520 460	410	0	90 100	195
12 days at 70°	2080	2250 2245	2410	790	770 900	1145	280	250 250	240
24 hrs. at 70° 2 reversals	1260	1485 1490	1720	420	308 410	500	97	120 130	160
13 days at 70°	2270	2120 2220	2050	1025	645 930	1130	270	236 295	380
28 days at 70°	3260	3060 3080	2950	1450	1450 1530	1710	410	745 625	720

TABLE XIII

Strength at Various Ages and Under

Different Storage Conditions

Group II

Storage Conditions	Mixtures	Ages 4 days 4 hrs.	4 days 8 hrs.	4 days 12 hrs.	5 days	8 days 4 hrs.	8 days 8 hrs.	8 days 12 hrs.	9 days
Normal Temperature	1:1:2	1240	1260	1280	1360	1800	1820	1840	1880
	1:2:4	360	380	400	440	670	668	690	720
	1:4:8	105	110	115	125	190	195	200	220
Initial Storage 1 Reversal	1:1:2	720	800	880	1060				
	1:2:4	180	230	290	430				
	1:4:8	40	50	70	110				
Initial Storage 2 Reversals	1:1:2					1080	1200	1320	1500
	1:2:4					200	230	340	480
	1:4:8					70	90	100	140
Loss of Strength due to 1 Reversal	1:1:2	520	460	400	300				
	1:2:4	180	150	110	10				
	1:4:8	65	60	45	15				
Loss of Strength due to 2 Reversals	1:1:2					720	620	520	380
	1:2:4					470	430	350	240
	1:4:8					120	105	100	80
[1]Per cent. of loss due to 1 Reversal	1:1:2	42	37	31	22				
	1:2:4	50	39	27					
	1:4:8	61	54	39	12				
Per cent. of loss due to 2 Reversals	1:1:2						33	28	20
	1:2:4						61	50	33
	1:4:8						53	50	35

[1] Per cent. value based on normal temperature values.

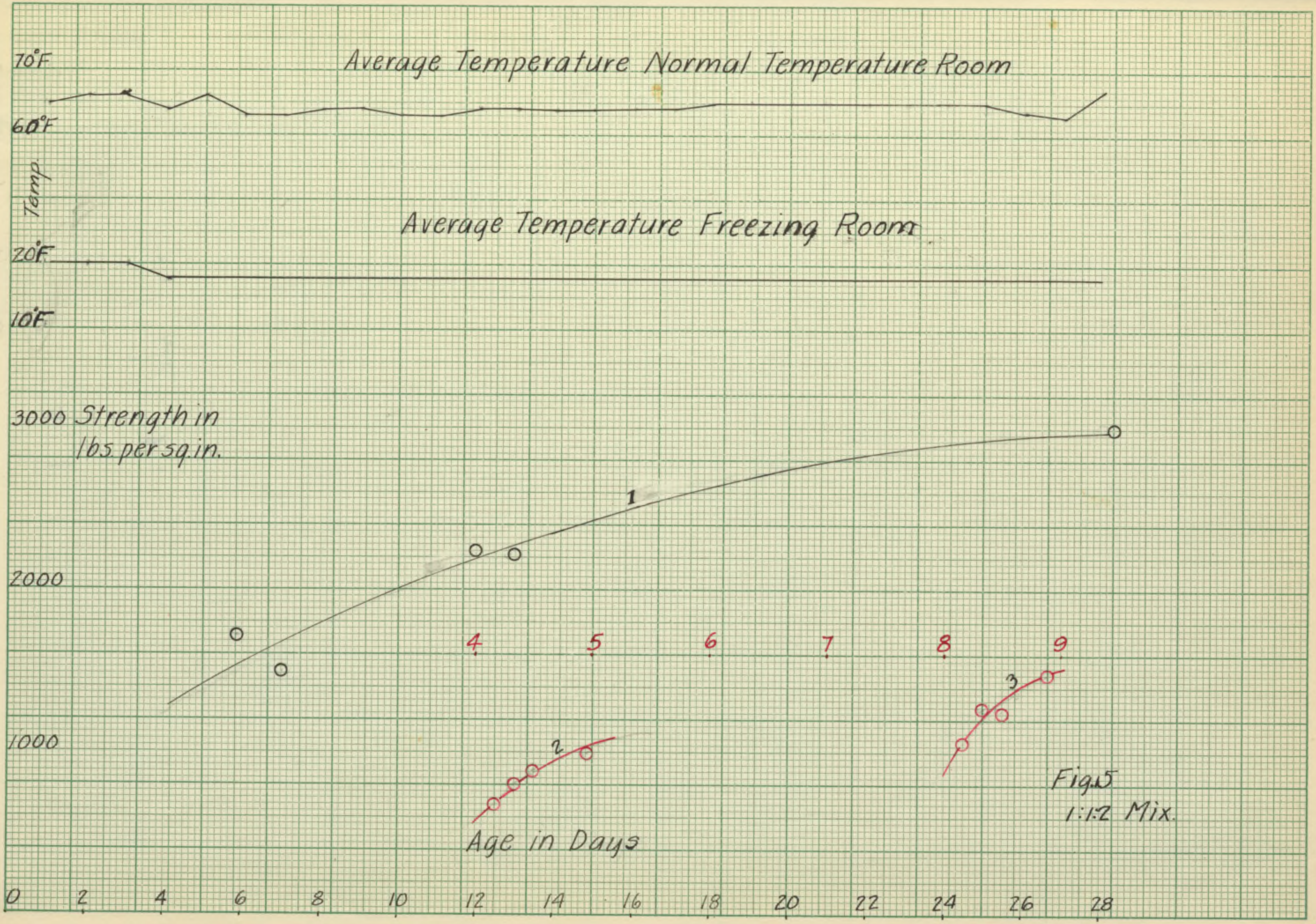
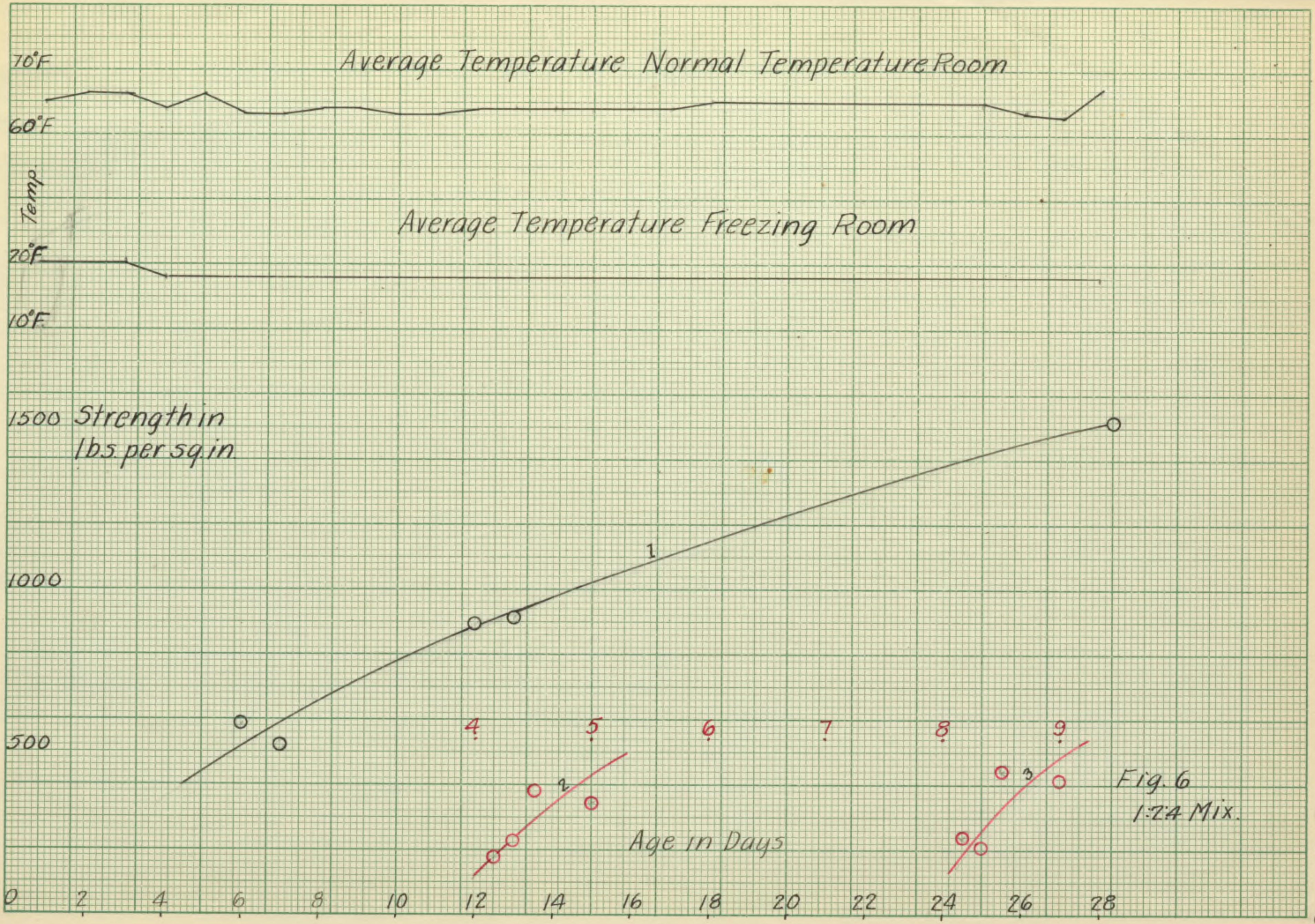
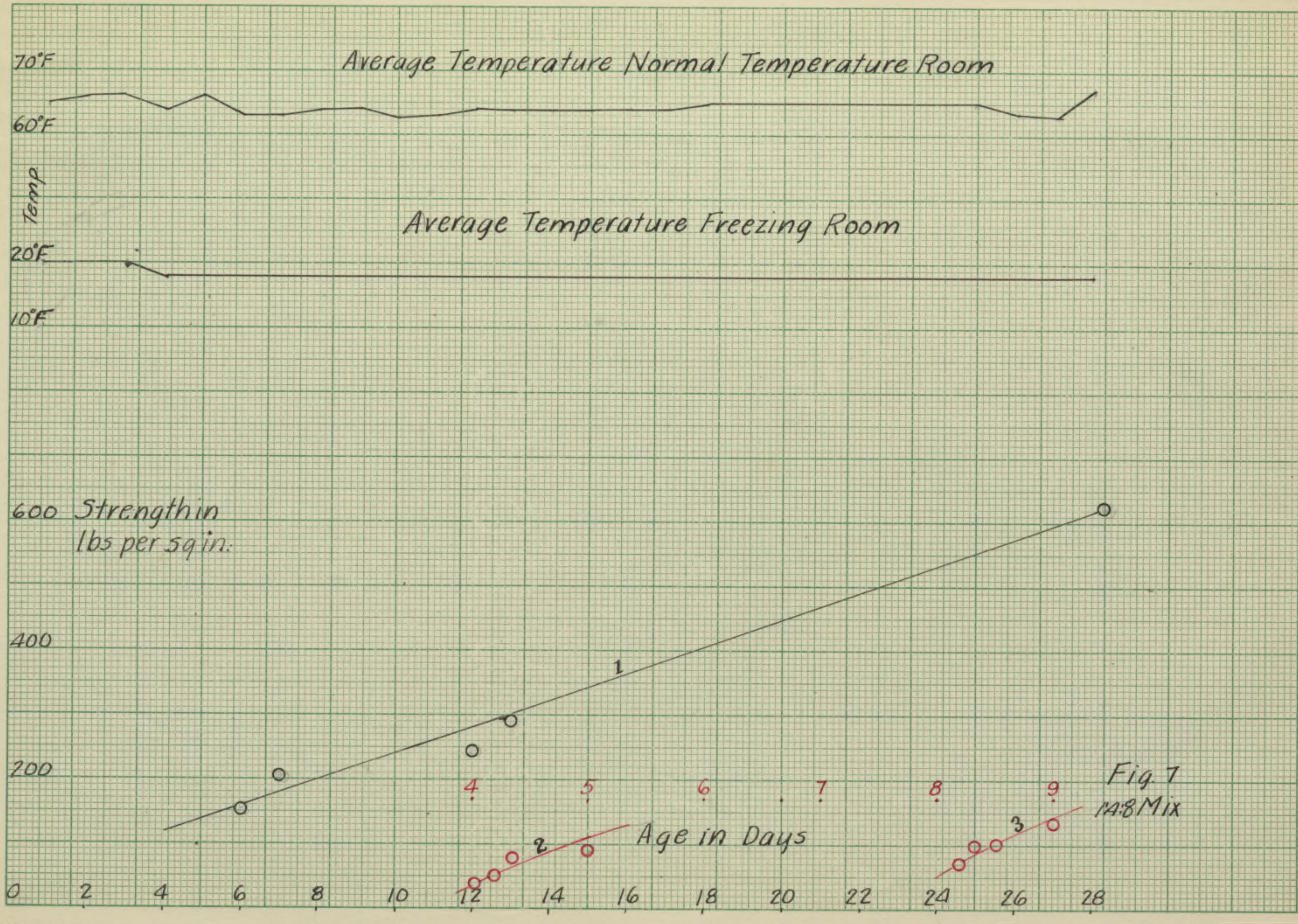


Fig. 15
1:1:2 Mix.



Average Temperature Normal Temperature Room
70°F
60°F
Temp.
Average Temperature Freezing Room
20°F
10°F
1500
Strength in lbs. per sq. in.
1000
500
1
2
3
4
5
6
7
8
9
Age in Days
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28

Fig. 6
1:2:4 Mix.



Average Temperature Normal Temperature Room
70°F
60°F
Temp
Average Temperature Freezing Room
20°F
10°F
600 Strength in lbs per sq in.
400
200
1
2
3
4
5
6
7
8
9
Age in Days
14:8 Mix
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28

Fig. 7

V. SUMMARY

The results of Group I give significant information as to the effect of alternate freezing and thawing on concrete of 1:1:2, 1:2:4 and 1:4:8 mixtures with initial storage periods of two, six, ten and fourteen days under a normal temperature of about 70° F.. In addition to this the data also furnish information relative to the effect on the strength of the three mixtures at the end of 28 days with the freezing and thawing conditions occuring after the different initial storage periods mentioned above.

The results of Group II furnish information concerning the effect of alternate freezing and thawing upon the strength of concrete for 1:1:2, 1:2:4 and 1:4:8 mixtures with initial storage periods of four, eight, twelve and twenty-four hours under a normal temperature of about 70° F. with freezing and thawing periods of two days at 70° F. and two days at 20° F. as compared with three alternations of one day at 70° F. and one day at 20° F. for Group I. Table XIV, page 39 gives the relative strengths of the specimens under a normal temperature of about 70° F. for the periods of 7, 14, 21 and 28 days for both Groups I and II. The results show that the rate of gain in strength varies with the richness of the mixture. The specimens in Group I show greater strength than those in Group II.

In Group I the compressive strength of the concrete for the 1:1:2 mixture and the periods of 7, 14 and 21 days may be taken as approximately 75%, 94% and 98% of the strength at 28 days respectively, while for the 1:2:4 and 1:4:8 mixtures, the values may be taken as 50%, 75% and 90% respectively.

In Group II the compressive strength of the concrete for the 1:1:2 mixture and the periods of 7, 14 and 21 days may be approximately taken as 50%, 80% and 95% of the strength at 28 days respectively. These percentages are lower than those given for this mixture in Group I. The leaner mixtures, 1:2:4 and 1:4:8 in Group II, show a slight variation. For the 1:2:4 mixture the representative strengths for 7, 14 and 21 days are represented by 40%, 65% and 85% of the strength at 28 days respectively and for the 1:4:8 mixture the percentages are 28, 50 and 75.

Under the similar conditions the specimens in Group I show greater strength over those of Group II and the rate of gain in strength varies with the richness of the mixture.

Table XV shows the loss of strength of the specimens at various ages and subjected to different temperature conditions based on the strength of specimens stored continously in the normal temperature room of about 70° F. For Group I, the specimens having had an initial set of 2, 6, 10 and 14 days, show a loss after one reversal of 11.1%, 10.8%, 7% and 3% respectively for the 1:1:2 mixture; for the 1:2:4 mixture this loss is practically constant having an average of about 11%. For the 1:4:8 mixture the loss varies from 11.1% for an initial set of 2 days to 6.7% for an initial set of 14 days.

In Group II, the length of initial set is much shorter, hence the loss in strength is greater. For the 1:1:2 mixture, the loss after one reversal as indicated by the table on page40 ranges from 42% for an initial set of 4 hrs. to 22% for an initial set of 24 hrs. for the 1:1:2 mixture. For the 1:2:4 mixture the loss varies from 50% for 4 hrs. to 2% for an initial set of 24 hrs. The loss for the 1:4:8 mixture is the greatest, being 61% for an initial set of 4 hrs. and 12% for an initial set of 24 hrs.

Group II after two reversals shows a greater percentage of loss except in the case of the richer mixture, 1:1:2, in which case the 1 and 2 reversals seem to have but little effect on the strength, being 39% for an initial set of 4 hrs. as compared with 42% for the same initial set and one reversal and 20% for an initial set of 24 hrs. as compared with 22% for the same initial set and one reversal. For the 1:2:4 mixture the extra reversal increased the loss of strength which is 70% for an initial set of 4 hrs. and gradually decreased with the increase in initial setting periods to 33% for an initial set of 24 hrs. The same characteristic occurs for the 1:4:8 mixture. This loss for this mixture varies from 63% for an initial set of 4 hrs. to 35% for an initial set of 24 hrs.

Hence we may be justified in saying that in general, the loss of strength of concrete after having been subjected to alternate freezing and thawing conditions varies (a) inversely as the richness of the mixture, (b) inversely as the length of the initial storage under normal temperature conditions, (c) as the number of reversals.

TABLE XIV

Group I

Strength at Various Ages Under Normal Temperature

Age	Strength			Per cent.[1]		
	1:1:2	1:2:4	1:4:8	1:1:2	1:2:4	1:4:8
7	2580	1165	335	75.5	49.5	48.6
14	3210	1680	510	94.0	78.0	74.0
21	3370	1980	610	98.5	92.0	88.5
28	3420	2150	690	100	100	100

Group II

7	1640	600	170	52	39.3	27.4
14	2400	990	320	80	64.6	51.5
21	2830	1280	470	94	83.5	75.5
28	3000	1530	620	100	100	100

[1]Per cent. values are based on twenty-eight day strengths.

TABLE XV

Group I

Strength at Various Ages and Under Different Storage Periods

One Reversal#

Initial storage periods	+Loss of strength in per cent. 1:1:2	1:2:4	1:4:8
2 days	11.1	11.4	11.1
6 "	10.8	11.7	8.7
10 "	7.0	11.3	7.4
14 "	3.0	11.3	6.7

Group II

One Reversal[1]

4 hrs.	42	50	61
8 "	37	39	54
12 "	31	27	39
24 "	22	2	12

Group II

Two Reversals

4 hrs.	39	70	63
8 "	33	61	53
12 "	28	50	50
24 "	20	33	35

One reversal in Group I consists of one day in the normal temperature room of about 70° F. and one day in the cold room of about 25° F.

+ The loss of strength in per cent. is based upon the strength of specimens stored in the normal temperature room only.

[1] One reversal in Group II consists of two days in the normal temperature room of about 70° F. and two days in the cold room of about 25° F.

VI. GENERAL CONCLUSIONS

The tests under Groups I and II discussed in this paper cover a range of temperature conditions varying from 20° F. to 70° F. The results give significant information concerning the effect of alternate freezing and thawing upon the strength of concrete. From a study of the results, it is believed the following general conclusions are justifiable.

(1) In general, for any of the three mixtures, and under a uniform temperature of about 70° F. there was an increase of strength with age within the limits of the tests. For this normal temperature, the rate of increase in strength decreases with the increase in age. The rate of increase varies with the richness of the mixture. For the specimens tested, under normal hardening conditions of from 60 to 70° F. the compressive strength of the concrete subjected toa uniform temperature at the ages of 7, 14 and 21 days may be taken as approximately 60%, 80% and 95% for the 1:1:2 mixtures, as 50%, 75% and 90% for the 1:2:4 mixture and as 40%, 65% and 85% for the 1:4:8 mixture, of the strength at twenty-eight days respectively.

(2) The loss in strength due to the alternate freezing and thawing conditions (a) decreases with the increase in the length of the initial setting period at a normal temperature, (b) increases with the number of reversals, and (c) decreases with the richness of the mixture. Table X, page 23shows clearly the characteristerics as mentioned herein. In Group II in which the specimens received an initial storage of 4 hrs., 8 hrs., 12 hrs. and 24

hrs. the loss of strength is much greater than that of Group I in which the initial storage periods were 2 days, 6 days, 10 days and 14 days. In Group II those specimens having had two reversals show greater loss of strength than those having had only one reversal for the same initial storage periods. Under similar conditions, the richer mixture shows less loss in strength.

(3) When concrete of a 1:1:2 mixture is stored at a normal temperature of about 70° F. for initial storage periods of four, eight, twelve and twenty-four hours, the percentage loss of strength after one reversal of one day at 20° F. and one day at 70° F. may be taken as about 40%, 35%, 30% and 20%, respectively, and the same after a second reversal. For a 1:2:4 mixture these percentage losses may be taken as about 50%, 40%, 25% and 10% after one reversal and 70%, 60%, 50% and 30% after two reversals. For a 1:4:8 mixture the percentage losses may be assumed as about 60%, 50%, 40% and 15% after one reversal and 70%, 55%, 50% and 35% after two reversals. The percentage values are based on the strength of the concrete for the same ages and stored at a normal temperature of about 70° F.